Missing baryons in shells around galaxy clusters

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Baryons in galaxy clusters

SZ effect: $$y = \int n_e(r)\sigma_T \frac{kT_e(r)}{m_e c^2} dl$$

X-ray: $$b_X(E) \propto \int n_p(r) n_e(r) \Lambda(E, T_e) dl$$

Measurements of the X-ray emission and Sunyaev-Zel'dovich effect indicate that **a significant fraction of baryonic mass is missing** from the hot ICM (e.g. Afshordi et al. 2007).

Usually two hypotheses are used to derive the baryon fraction:

- hydrostatic equilibrium
- thermal equilibrium: Tp=Te

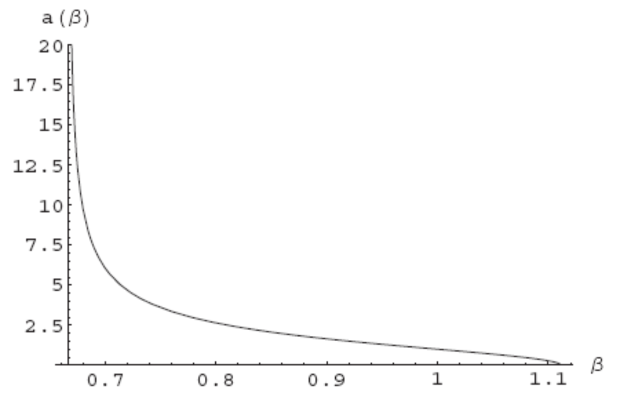
Cluster outskirts

External cluster regions show less X-ray emission with respect to the center, where the density is much higher. This lower emission translates in lower statistics in available X-ray observations.

Assumptions:

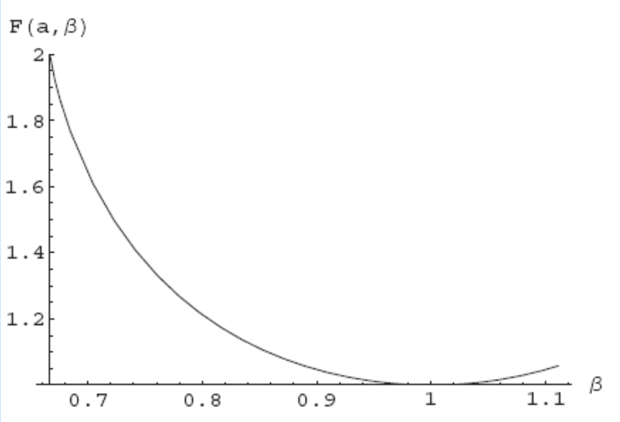
$$n(r) = n_0\left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3\beta}{2}}$$

$$kTdn = -\frac{GM_{tot}(r)\mu m_p n(r)dr}{r^2}$$



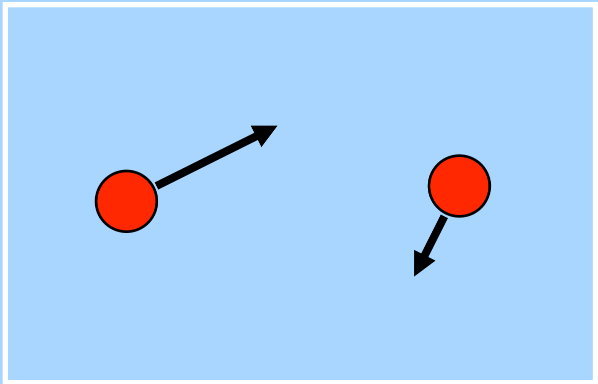
$$f(r) = \rho(r)/\rho_{tot}(r)$$

$$F(r,\beta) = \frac{f(r)}{f(r_c)} \qquad a = r_c \cdot \sqrt{\frac{9\beta - 10}{2 - 3\beta}}$$



$$F(a,\beta) = \sqrt{(4 - 3\beta)^{4-3\beta}(3\beta - 2)^{3\beta-2}}$$

Coulomb mean-free-path



$$\frac{e^2}{r} \approx k_B T$$

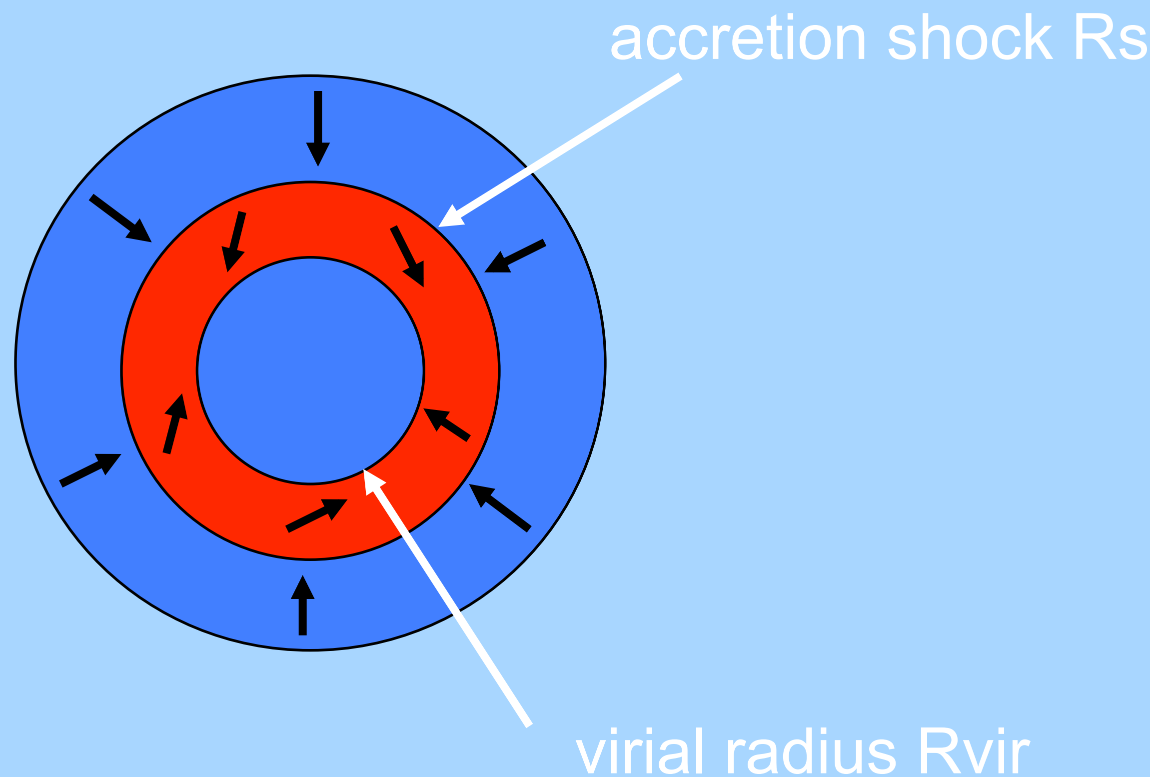
$$l = \frac{1}{nr^2} \approx \frac{k_B^2 T^2}{ne^4}$$

$$l = \frac{3^{3/2} k_B^2 T^2}{4\pi^{1/2} ne^4 \ln \Lambda}$$

Coulomb mean-free-path in outskirts:

$$l = 3Mpc \cdot \left(\frac{T}{10keV} \right)^2 \cdot \left(\frac{10^{-5} cm^{-3}}{n} \right)$$

Accretion model



- collisionless region

- collision regions

for similar view of a quasar model (Meszaros, Ostriker 1983)

Missing baryons in a shell around cluster

The proton random motion energy is of the order of the gravitational temperature:

$$T_{gr} = \frac{GM(R_{vir})m_p}{k_B R_{vir}}$$

The proton will be collisionless if $l > L$

$$L = H_0^{-1}\sqrt{\frac{k_B T_{gr}}{m_p}}$$

L is the maximal distance, which the proton can cover during the cluster age

The collisionless condition is equivalent to the inequality:

$$n < \frac{3^{3/2} k_B^2 T_{gr}^2}{4\pi^{1/2} L e^4 \ln \Lambda}$$

Cluster mass

Mass of gas shell between
accretion shock and virial radius:

$$M_{shell}^{gas} = \frac{4\pi}{3} R_{vir}^3 \left(\frac{R_s^3}{R_{vir}^3} - 1 \right) n m_p$$

condition on n:

$$M_{shell}^{gas} < \sqrt{\frac{6\pi}{\Delta_c}} \left(\frac{R_s^3}{R_{vir}^3} - 1 \right) m_p^3 \frac{G^2 M^2 (R_{vir})}{e^4 \ln \Lambda}$$

If the missing baryons are situated in the collisionless shell:

$M_{shell}^{gas} / M(R_{vir}) = f_b - f$

$$M(R_{vir}) > \sqrt{\frac{\Delta_c}{6\pi}} \frac{(f_b - f) \ln \Lambda}{\frac{R_s^3}{R_{vir}^3} - 1} \frac{e^4}{G^2 m_p^3}$$

$$M(R_{vir}) > 3 \cdot 10^{15} M_{sun}$$

Dimension mass

$$\frac{e^4}{m_p^3 G^2} = 1.3 \cdot 10^{15} M_{sun}$$

Time scale for protons and electrons to equilibrate:

$$t_{eq}(p,p) \approx \sqrt{\frac{m_e}{m_p}} \cdot t_{eq}(p,e)$$

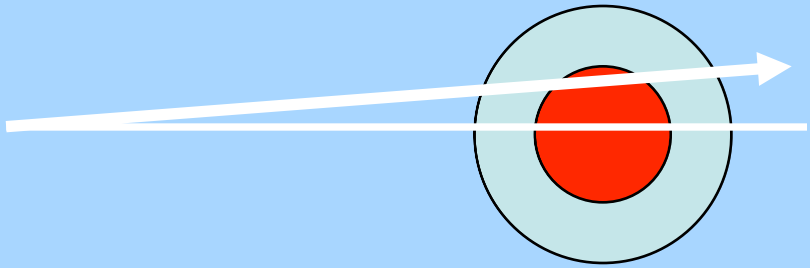
The electron will be cold between the accretion shock and virial radius if $t_{eq}(p,e) > H_0^{-1}$

Condition on M(Rvir): $M(R_{vir}) > \sqrt{\frac{\Delta_c}{6\pi}} \sqrt{\frac{m_e}{m_p}} \frac{(f_b - f)\ln\Lambda}{\frac{R_s^3}{R_{vir}^3} - 1} \frac{e^4}{G^2 m_p^3}$

$$M(R_{vir}) > 7 \cdot 10^{13} M_{sun}$$

Halo of EUV emission

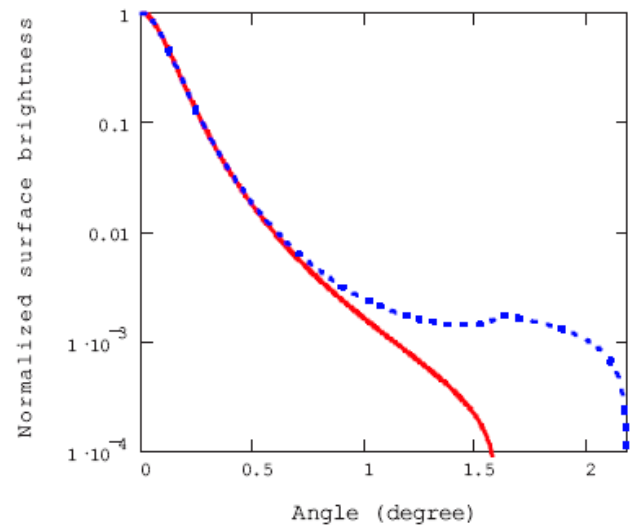
Spectral surface brightness along a particular line of sight:



$$b(E) \propto \int n_e^2(r)\Lambda(E,T_e)dl$$

Normalized spectral surface brightness:

$$B(\theta) = \frac{b_h(\theta) + b_c(\theta)}{b_h(0) + b_c(\theta)}$$



Normalized spectral brightness for the Coma cluster: the hot gas (solid line), the hot gas + the baryonic shell (dashed line).

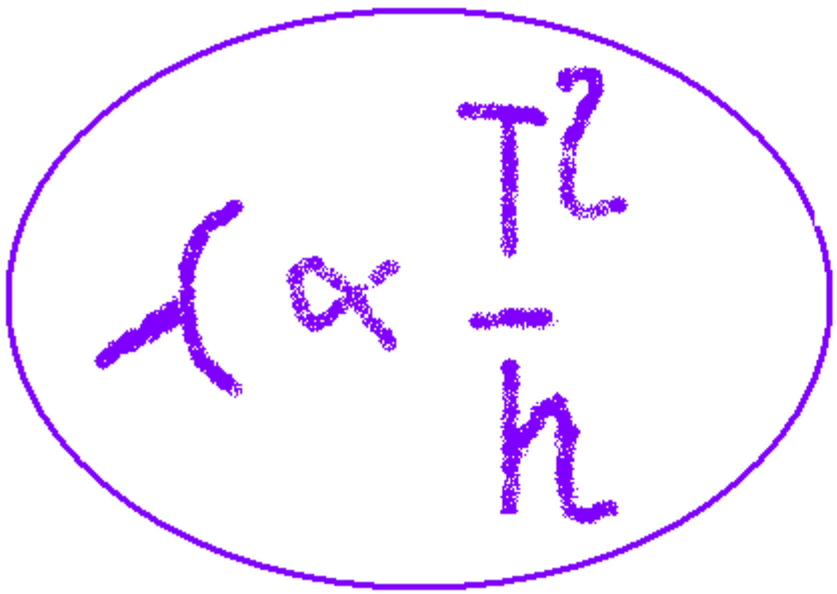
at observed energy 0.1keV

Conclusions

The protons below the shock will be able to accrete into the galaxy cluster on a Coulomb time scale, which may be longer than the cluster age, and baryons may accumulate in the cluster outskirts.

Only for Fun

Equation for Coulomb mean-free path:



Rotated equation

face of a smoker???